

Supporting Information for “Imaging elastodynamic and hydraulic properties of in-situ fractured rock: An experimental investigation exploring effects of dynamic stressing and shearing”

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Introduction This supporting information contains figures that clarify how permeability is calculated and hydraulic and mechanical properties during shearing phases from experiment p4975. Furthermore, we show how velocity and RMS amplitude evolve with outlet flow rate and normal stress oscillations, and how change in RMS amplitude relates to change in permeability.

In Figure S1 we measure the effective permeability, k , by calculating the flow rate over a 2 s window. For pore pressure oscillations, we start 10 s after the oscillation to ensure

that permeability measurement is not affected by the P_p oscillation and/or by storage effects.

Figures S2 and S3 show how the flow rates evolve with various shearing rates in experiment p4975. We attribute the smaller flow rates in the second shearing phase ($\approx 1/2$ that of the first shearing phase) to be in response to the comminuted grains clogging the fracture.

The relationship between these parameters in the beginning, middle, and end of the oscillation are presented in Figure S4. This figure also includes hysteresis plots that show how the wave velocity vary as a function of stress. Throughout this long oscillation the velocity-flow hysteresis loop generally evolves to a lower velocity and lower flow rate and the loop becomes slightly more closed. We also observe this general decrease in wave velocity as a function of applied stress throughout the history of the oscillation. If the oscillation persists long enough, the wave velocity modulations reach a steady-state. These observations demonstrate the magnitude of changes we are characterizing and also reinforce that the fracture is continuously evolving during the dynamic perturbations; contacts undergo compression and tension resulting in changing flow paths across the fracture.

For elastic waves that travel across fractures the transmitted amplitude provides information on contact stiffness and area. Our data show that changes in RMS amplitude, $\Delta A/A_0$, evolve in a similar manner to changes in p-wave velocity for both types of effective dynamic stressing (see Figure S5). In the post-fracture case p4975 results show that the change in transmitted p-wave amplitude becomes more negative with increasing normal stress amplitude; this trend is less obvious with pore pressure oscillation amplitude. Fur-

thermore, there is little variation in these results with the order in which the oscillations were conducted. The situation is different for experiments p4966 in that the results are very scattered for normal stress oscillations and more coherent for pore pressure oscillations. The order of oscillation is most pronounced for oscillation amplitudes > 0.25 MPa, subsequent sets are less nonlinear. Surprisingly, normal stress oscillations in post-shear 1 of experiment p4966 produce positive changes in RMS amplitude, which contradict our findings with respect to $\Delta c/c_0$. Another interesting observation is that progressive shearing creates conditions that produce less nonlinearity. These differences are likely due to the complexity of fracture roughness and changes in contact stiffness with shear.

The averaged change in RMS as a function of $\Delta k/k_0$ is plotted in Figure S6. These plots show a complex relationship between the transmitted energy and fracture hydraulic properties. Normal stress oscillations of 40 Hz frequency consistently produce positive nonlinearity values. This and our observation that nonlinearity decreases with shearing are in fact physical rather than artifacts of data analysis. Pore pressure oscillation results are more scattered but show a similar relationship as normal stress oscillations, but the underlying elasto-hydraulic mechanisms require further experimental investigation.

Figure S1. Example of dynamic stressing and the corresponding flow rate measurements for a set of pore pressure oscillations in experiment p4975. Note that the plots (a) and (b) are decimated for clarity. (a) Imposed pore pressure oscillation at inlet and fixed pore pressure at the outlet. Pressure conditions before and after the oscillations are identical. (b) Measured flow rates at the fracture inlet (blue line) and outlet (red dashed line). Notice the small time lag (≤ 2 s) between the maxima of the inlet and outlet flow rates. (c) Permeability at steady-state and during the pore pressure oscillation. In the calculation of permeability we impose a threshold between the flow rates to ensure steady-state flow ($Q_A - Q_B \leq 5\%$). It is reasonable to assume that even at relatively low frequency oscillations, there is effectively no steady-state flow during the imposed oscillations.

Figure S2. First shearing for phase during experiment p4975. There are noticeable spikes in inlet flow rate Q_A in response to changing displacement rate (LP disp).

Figure S3. Second shearing for phase during experiment p4975. There are spikes in inlet flow rate Q_A and a smaller, delayed increase in outlet flow rate Q_B in response to changing displacement rate (LP disp).

Figure S4. Evolution of the fracture during a 1 MPa, 1 Hz normal stress oscillation during the first cycle (a), middle cycle (b), and last full cycle (c). The relationship between velocity and RMS Amplitude with outlet flow rate track each other throughout the oscillation, resulting in decreased flow.

Figure S5. RMS amplitude for direct-path receiver as a function of permeability change for σ_{NS} and P_P oscillations. Data point shapes oscillation order. RMS amplitude decreases with oscillation amplitude and show little variation with order for experiment p4975. Order of oscillation is most pronounced for oscillation amplitudes > 0.25 MPa, Subsequent oscillation sets are less nonlinear; surprisingly, normal stress oscillations in post-shear 1 in p4966 produce positive changes in RMS amplitude. Furthermore, progressive shearing creates conditions that produce less nonlinearity, likely due to the complexity of fracture aperture and changes in contact stiffness.

Figure S6. RMS amplitude averaged over all receivers as a function of permeability change for σ_{NS} and P_P oscillations. Data point shapes correspond to oscillation frequency and sizes to amplitude. There is a familiar trend that the average RMS amp. decreases with oscillation amplitude and frequency, except at high frequencies where there is anomalous behavior. Shearing the fracture weakens the relationship with relative permeability change.